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<u>C E R T I F I C A T I O N</u>

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I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

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1   CONTROL FOR A BRUSHLESS DC MOTOR

2

3   [001] The present invention relates to a device and a method

4   for controlling a brushless DC motor.

5

6   [002] A device of this type conventionally comprises an AC/DC

7   inverter supplied by an intermediate direct voltage circuit

8   for feeding stator windings of the DC motor and a pattern

9   generator for controlling switches of the AC/DC inverter

10 having a periodic switching signal pattern such that the

11 stator windings in the motor generate a rotating magnetic

12 field in the permanent magnets of the rotor attempt to align

13 themselves. The torque which such a motor is capable of

14 delivering depends on the angle between the permanent

15 magnetic field of the rotor and the magnetic field of the

16 stator windings in advance thereof. For optimal efficiency of

17 the motor, the currents fed by the AC/DC inverter into the

18 stator windings and the electromotive force (emf) induced

19 therein by the turning of the rotor should be in phase. This

20 means that the control voltage of the emf of the motor is

21 more or less in advance. The lead angle at which the motor

22 achieves the optimal efficient depends on the load of the

23 motor, i.e., the torque exerted thereby and the speed. In

24 order to operate the motor at the highest possible

25 efficiency, load and speed are therefore normally measured

26 and a lead angle known as optimal for a given combination of

27 values of the load and speed (hereinafter calls the operating

28 point of the motor) is set. The load is known to be

29 proportional to the peak current of the individual stator

30 windings which is why, to determine the load, the peak

31 current is measured using an electronic peak value detector

32 and the load is calculated therefrom.

33

1   [003] However, it is especially difficult to detect the peak
2   current in cases of pulse-width-modulated control of the
3   AC/DC inverter and low motor loads since, as a result of the
4   small pulse widths, fast and therefore expensive comparators
5   must be used in a peak value rectifier so that this can
6   exactly reproduce the peak current at low pulse duty factors.
7
8   [004] It is the object of the present invention to provide a
9   device and a method for controlling a brushless DC motor
10 which allows the DC motor to be operated with high efficiency
11 using simple and inexpensive means.
12
13 [005] The object is solved by a method having the features of
14 claim 1 or a device having the features of claim 6.
15
16 [006] In contrast to the peak current strength, the average
17 current strength can be detected exactly without any
18 difficulties even at low loads but is not in any single-
19 valued relationship to the motor load because the efficiency,
20 that is the ratio of the product of load and speed to the
21 consumed electrical power, depends on the lead angle.
22 Nevertheless, this can surprisingly be used in an iterative
23 method to adjust the operating point of a brushless DC motor.
24
25 [007] The desired value of the lead angle is preferably that
26 value of the lead angle which maximises the efficiency of the
27 motor for the allocated values of the speed and average power
28 requirement. If the lead angle is approximated to this
29 desired value, the resulting improvement in the efficiency of
30 the motor for the same average power requirement of the motor
31 results in an increase in the mechanical power, i.e. in an
32 increase in the speed for the same load. By returning the
33 speed to its desired value again by varying the average
34 terminal voltage of the motor, the optimal operating point of

1   the motor for this desired speed is reached in the course of

2   several iterations.

3

4   [008] The desired value of the lead angle is preferably

5   determined using a characteristic map which specifies the

6   lead angle with the highest efficiency for a plurality of

7   operating points of the motor each defined by a speed and an

8   average power requirement. Such a characteristic map

9   generally specific for the design of the motor is preferably

10   first determined empirically and can be provided for the

11   control according to the invention in the form of a memory

12   module which gives the respectively optimal lead angle for

13   the various operating points.

14

15   [009] Since such a characteristic map can only comprise a

16   limited number of discrete operating points, in general the

17   load angle (lead angle) for an actual speed and average power

18   requirement is obtained from the characteristic map by

19   interpolation.

20

21   [010] In order to influence the average power requirement of

22   the motor, the average terminal voltage applied thereto is

23   preferably varied by pulse width modulation.

24

25   [011] A control device suitable for carrying out the method

26   comprises an AC/DC inverter for feeding the DC motor, a

27   pattern generator for controlling the switches of the AC/DC

28   inverter having a periodic switching signal pattern of

29   variable frequency and phase, which has an input for a

30   representative signal for an instantaneous phase position of

31   the rotor of the DC motor, wherein the pattern generator has

32   means for detecting the average current strength delivered by

33   the AC/DC inverter and means for adjusting a phase offset

34   between the phase position of the rotor and the switching

1 signal pattern depending on the detected average current

2 strength and the speed of the motor.

3

4 [012] In order to counteract any drift of the motor speed in

5 the event of a correction to the phase offset, means are

6 preferably provided for regulating an average terminal

7 voltage of the motor using a desired speed.

8

9 [013] The means for adjusting the phase offset preferably

10 comprise a phase-locked loop (PLL) circuit which can be

11 locked to the frequency of the input signal representative of

12 the phase position of the rotor. For adjusting the phase

13 offset control means are provided for predefining a target

14 phase offset depending on the detected power and speed of the

15 motor. These control means preferably include the afore-

16 mentioned storage device for the characteristic map, which

17 specifies for a plurality of operating points, respectively

18 one target phase offset which minimises the efficiency of the

19 motor.

20

21 [014] The speed of the motor can be detected using a speed

22 sensor coupled to the motor; preferably however the means for

23 adjusting the phase offset comprise means for deriving the

24 speed from the input signal representative for the phase

25 position of the rotor.

26

27 [015] The means for adjusting the phase offset can be divided

28 into a desired value transmitter which specifies a desired

29 value of the phase offset for the actual operating point and

30 generates a representative signal for this desired value and

31 a regulator for matching the actual phase offset to this

32 desired value using the representative signal. At the same

33 time, the representative signal can have values above and

34 below a representative value for a phase offset of $0°$ so that

1   standard processing of signals representative for positive

2   and negative phase offsets is possible in the regulator.

3

4   [016] Further features and advantages of the invention are

5   obtained from the following description of exemplary

6   embodiments with reference to the appended figures. In the

7   figures:

8

9   [017] Figure 1 is a block diagram of the control device

10   according to the invention and a brushless DC motor

11   controlled thereby;

12

13   [018] Figure 2 is a schematic circuit diagram of an AC/DC

14   inverter used in the control device in Fig. 1;

15

16   [019] Figure 3 shows the time sequence of the switching

17   states applied cyclically repeatedly to the motor; and

18

19   [020] Figure 4 is a diagram which illustrates the migration

20   of the operating point of a brushless DC motor controlled

21   using the device according to the invention.

22

23   [021] In the block diagram in Fig. 1, 1 designates a

24   brushless DC motor whose rotor has n = 4 pairs of poles. The

25   DC motor 1 i supplied by an AC/DC inverter 7 which is shown

26   in greater detail in Fig. 2. This comprises six switches SU1,

27   SV1, SW1, SUZ2, SV2, SW2 of which the switches SU1, SV1, SW1

28   are arranged between a positive supply terminal (+) and a

29   phase U, V or W of the motor 1 and the switches SU2, SV2, SW2

30   are each arranged between one of these three phases and a

31   negative supply terminal (-). The switches can be IGBTs known

32   per se with a suppressor diode connected in parallel.

33

1   [022] The switches of the AC/DC inverter are controlled by a

2   control circuit 6 which applies six different switching

3   states to the switches in a cyclically recurrent manner,

4   these being explained in further detail with reference to

5   Fig. 3.

6

7   [023] A Hall sensor 2 is located in the immediate vicinity of

8   the rotor of the motor 1 to detect the field of each

9   individual pole of the rotor which passes thereby. The Hall

10 sensor 2 delivers an output signal which has an ascending

11 flank in each case when passing a first type of pole and a

12 descending flank when passing the other type of pole. The

13 frequency f of the output signal of the Hall sensor 2 is thus

14 n times the rotational frequency of the motor 1.

15

16 [024] The output signal of the Hall sensor 2 is applied to a

17 first input of a phase comparator 3 whose second input is

18 supplied with a comparison signal whose formation will be

19 explained. The phase comparator 3 can be formed, for example,

20 by an electronic counter which begins to count pulses of a

21 clock signal whenever a descending signal flank arrives from

22 the Hall sensor, the frequency of this signal being a

23 multiple of the frequency f, until a descending signal flank

24 is received at the second signal input and outputs the

25 counter result as the measured value for a phase difference

26 between the two signals.

27

28 [025] The output signal of the phase comparator 3 forms the

29 non-inverted input signal of a differential amplifier 8 to

30 whose inverting input is applied a representative desired-

31 value signal provided by a microcontroller 21 for a desired

32 phase offset between the pattern of the switching states and

33 the output signal of the Hall sensor. The level of this

34 desired-value signal is linearly relate to the desired lead

1 angle and can have values in a range whose limits should each

2 correspond to desired lead angles smaller or larger than 0°.

3 The lower limit preferably corresponds to a desired lead

4 angle of $-2\pi/3$ and the upper limit corresponds to a lead

5 angle of $+4\pi/3$ so values of the desired lead angle around 0°

6 can be adjusted by continuously varying the level of the

7 desired value signal.

8

9 [026] Connected to the output of the differential amplifier 8

10 is a proportional/integral controller consisting of a

11 weighting part 9 which multiplies the output signal of the

12 difference amplifier 8 with a pre-determined weighting

13 factor, and an integrator 10 for integrating the output

14 signal of the differential amplifier. The additively

15 superposed output signals from the weighting part 9 and

16 integrator 10 are fed to a voltage-controlled oscillator 5 as

17 a frequency-controlled signal together with further

18 contributions added in an adder 11.

19

20 [027] In addition to the phase comparator 3, a period

21 measuring circuit 12 is connected to the output of the Hall

22 sensor 2, which circuit measures the time between two

23 successive descending flanks of the signal from the Hall

24 sensor 2 and delivers this as an output signal to an average

25 value circuit 13 and a first shift register 14. Connected to

26 the output of the first shift register is an input of a

27 second shift register 15 and a second input of the average

28 value circuit 13; connected to the output of the second shift

29 register is a third shift register 16 and a third input of

30 the average value circuit 13, and at the output of the third

31 shift register a fourth input of the average value circuit

32 13. With each new period measured value supplied by the

33 measuring circuit 12, this triggers the shift registers 14,

34 15, 16 so that these take over and output the measured value

1   respectively applied to their input. Thus, the four most
2   recent measured values of period durations of the Hall sensor
3   signal are always applied to the inputs of the average value
4   circuit 13. The average value circuit 13 delivers the average
5   of these measured values at its output. (In general, if the
6   number of pairs of rotors is n, n inputs and n - 1 shift
7   registers are always provided so that averaging is performed
8   over the number of periods of the Hall sensor signal which
9   corresponds to a complete revolution of the rotor). Cyclic
10 fluctuations in the period duration which can result from
11 non-uniformities in the arrangement of the four pairs of
12 poles of the rotor are thus eliminated in the output signal
13 of the average value circuit 13. This output signal makes a
14 substantial contribution to the input voltage of the voltage-
15 controlled oscillator 5. Thus, after two passages of the
16 rotor through the reference position, an input voltage is
17 applied to the oscillator 5 which is not far removed from the
18 input voltage which would be established in the steady-state
19 mode and the frequency of the oscillator 5 can rapidly lock
20 to that of the rotor.
21
22 [028] The output of the average value circuit 13 is further
23 connected to a difference circuit 18, on the one hand
24 directly and on the other hand via a fourth shift register 17
25 which is triggered in a similar manner to the shift registers
26 14 to 16 so that the difference circuit 18 delivers the
27 difference between two successive averaged periods of the
28 Hall sensor signal as an output signal. The output signal of
29 the difference circuit 18 thus corresponds to the average
30 variation of the period duration and indicates an accelerated
31 or slowed running of the motor 1. This accelerated or slowed
32 running is taken into account by adding the output signal of
33 the difference circuit 18, weighted by a factor of 0.5 in a
34 weighting part 19, to the afore-mentioned contributions to

1 the input signal of the oscillator 5 in the adder. Thus, the

2 oscillation of the oscillator 5 already allows for a

3 variation of the period duration which is to be expected in

4 extrapolation of the past but has not yet been measured.

5

6 [029] The voltage-controlled oscillator 5 delivers an

7 oscillation whose frequency in the steady-state mode is six

8 times as high as that of the Hall sensor signal. A 1/6 count-

9 down oscillator 20 produces the comparison signal supplied to

10 the phase comparator 3 herefrom. The control circuit 6

11 receives the output signal with the frequency 6f from the

12 voltage-controlled oscillator 5 and derives the control

13 signals for the switches of the AC/DC inverter 7 from this.

14 In the time diagram in Fig. 3 the oscillation of the voltage-

15 controlled oscillator 5 is designated by VCO. The control

16 circuit 6 responds to its ascending flank by changing from

17 one of six cyclically successively produced switching states

18 a, b, c, d, e, f to the next.

19

20 [030] For each of the switching states a to f Figure 3 shows

21 the state of the switch of the AC/DC inverter 7 and the

22 voltages resulting therefrom at the phases U, V, W of the

23 electric motor 1. In state a the switches SU1, SW1 are

24 closed. The switches SU2, SW2, SV1 are open and the switch

25 SV2 is opened and closed in pulsed mode, the pulse duty

26 factor being specified by a power control signal which the

27 control circuit 6 receives from the microcontroller 21.

28 According to the pulse duty factor of the switch SV2, current

29 flows through the phases U, V or W, v of the motor and the

30 resulting magnetic fields are superposed to form a space

31 vector u_a. In the following switching state b, the switches

32 SV2, SW2 are open, SU2, SV1, SW1 are closed and SU1 is pulse-

33 width-modulated with a pulse duty factor specified by the

34 power control signal of the microcontroller 21; accordingly

1   current flows through the phases U, V and U, W and results in

2   a space vector u_b which is turned through 60° in the

3   anticlockwise direction compared with u_a. The closed, open,

4   pulse-width-modulated, states of the switches for states c,

5   d, e, f and the resulting current distributions and space

6   vectors can be read off from Fig. 3 and do not need to be

7   explained here in detail. It is important that six periods of

8   the VCO signal produce a rotation of the space vector through

9   360°.

10

11 [031] Naturally, the states of the AC/DC inverter 7

12 controlled by the control circuit 6 can be different from

13 those shown in Fig. 3, in particular, although less

14 preferred, a state pattern can be considered where each phase

15 U, V, W of the motor 1 is kept current-free for the length of

16 respectively one state by opening both allocated switches,

17 then connected to the positive supply voltage for the length

18 of two states, then kept current-free for the length of one

19 state again and finally connected to the negative supply

20 terminal for the length of two states and the three phases

21 are phase-shifted with respect to one another by respectively

22 two states.

23

24 [032] The efficiency of the electric motor 1 depends on the

25 lead angle between the magnetic field generated by the

26 windings of its state and the rotor rotating in this field.

27 For each operating point characterised by a speed and a

28 torque or in an equivalent manner, by a speed and a

29 mechanical power, there is an optimal lead angle which can be

30 determined empirically, for example, for a specific motor

31 model. Since, as has already been explained, the

32 determination of the peak current from which the load (the

33 torque) could be uniquely calculated, is complex, a different

34 approach is selected in the control device according to the

1 invention. In this case, the microcontroller 21 detects the

2 electrical power requirement of the motor 1, for example, as

3 shown in Fig. 1, using a series resistor 22 disposed in the

4 intermediate circuit of the AC/DC inverter 7 to which a

5 voltage proportional to the current strength of the

6 intermediate circuit is applied. If the intermediate-circuit

7 voltage is assumed to be constant, measurement of this

8 current strength is sufficient to determine the electrical

9 power requirement; on the other hand, it can be provided that

10 the microcontroller 21 also measures the intermediate-circuit

11 voltage and calculates the power requirement as a product of

12 intermediate circuit voltage and current strength. The speed

13 of the motor 1 is determined by the micro-controller 21 from

14 the output signal of the adder 11 which is proportional

15 hereto.

16

17 [033] A characteristic map which gives the optimal lead angle

18 for a set of operating points is stored in a memory module 23

19 connected to the microcontroller 21. This set of operating

20 points is selected in a manner known per se so that for all

21 practically relevant operating points of the motor 1 not

22 contained therein, the respectively optimal lead angle can be

23 calculated by interpolation in the microcontroller 21.

24

25 [034] The operating mode of the microcontroller is explained

26 with reference to Fig. 4. The figure is a three-dimensional

27 diagram in which a curved surface K represents the

28 relationship between speed U, mechanical power P and optimal

29 lead angle θ stored in the characteristic map. A point P0 in

30 this diagram represents an arbitrary starting point of the

31 regulating method executed by the microcontroller 21. This is

32 characterised by a value of the speed deduced by the

33 microcontroller from the output signal of the adder 11, an

34 (arbitrary) lead angle θ which the microcontroller 21 applies

1   as the desired value to the differential amplifier 8, and a

2   mechanical power P of the motor which the microcontroller 21

3   estimates from the consumed electrical power by multiplying

4   with a known efficiency η of the motor. The efficiency η is

5   that efficiency achieved by the motor at the given speed with

6   an optimally adjusted lead angle θ. At the point P0 the lead

7   angle is higher than the optimal value so that the mechanical

8   power of the motor is actually lower than the value estimated

9   by the microcontroller 21. However, this is not disturbing

10 for the purposes of the method. Using the values of the speed

11 and mechanical power thus obtained the microcontroller 21

12 determines the optimal lead angle corresponding to the

13 operating point using the characteristic map K (where it

14 imputes the estimated value of the mechanical power to be the

15 true value) and predefines the lead angle thus determined as

16 the desired value to the differential amplifier 8. Thus, the

17 point P1 is in the diagram in Fig. 4 is reached.

18

19 [035] Since the mechanical power of the motor assumed by the

20 microcontroller is based on an approximation, in reality no

21 point is reached on the surface K but the efficiency of the

22 motor 1 is improved by correcting the lead angle.

23 Consequently, the speed and/or mechanical power of the motor

24 increase and the estimated operating point migrates towards

25 P2. The microcontroller 21 now recognises that the desired

26 speed is exceeded and the control circuit 6 reduces the pulse

27 duty factor preset by the afore-mentioned power control

28 signal. If the lead angle remains the same, the speed and/or

29 power decrease again and the point P3 is reached. At this

30 point, as previously at point P0, the optimal lead angle is

31 estimated from the characteristic map and set for the assumed

32 operating point. The procedure is repeated iteratively until

33 it finally converges to the point P where the lead angle θ is

1 optimally adjusted and the efficiency of the motor is

2 actually equal to θ.

3 [036]

4